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Scalable hybrid beam combining of kilowatt fiber amplifiers into a 5-kW beam

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ABSTRACT

We report on the hybrid beam combination of five unpolarized fiber lasers with the output power of 5.02 kW. Each fiber laser provides the output with average power of 1.1 kW and full width half maximum (FWHM) linewidth of 0.3 nm. The five beams with different wavelength are first split into two orthogonal linear polarizations, spectrally combined by dual multilayer dielectric (MLD) diffraction gratings in turn, finally combined into a single beam using a polarization beam combiner. This hybrid system features a combining efficiency of 91.2%, the beam quality of M^2=2.96×1.52, and excellent prospects for significant power scaling.

1. Introduction

High power fiber lasers are attractive sources for various applications due to their excellent beam quality, high efficiency and distributed thermal loading. While the power level has developed extremely rapidly, the limitations in a single fiber laser have emerged, such as nonlinear optical effects, thermal lens effect, or damage [1]. The idea that combining several laser beams into a single beam can overcome the above limitations. Great achievements of SBC have been made in different ways. Coherent beam combination (CBC) based on diffraction optical elements (DOE) can preserve excellent beam quality. However, it requires complex feedback control systems [2]. By constrast, spectral beam combination (SBC) is robust and simple without the requirement of the active control. Great achievements have been made by several teams. By using volume Bragg gratings, a 5-channel SBC system is reported with a combined output power of 0.75 kW and ultra-high-brightness [3]. Four fiber lasers are spectrally combined into an 8.2 kW beam using a polarization-independent diffraction grating [4]. Meanwhile, higher power scaling can be also achieved by combining more fiber laser beams. Up to 12 individual fiber lasers are combined into a single 3.1 kW beam with excellent beam quality [5]. By combining 96 individual fiber lasers into a single beam, 30 kW output with a beam quality of M^2=1.6×1.8 is achieved [6]. This is the new record of both power and number of combined lasers by SBC.

In order to avoid the dispersion-induced degeneration of beam quality, single-grating SBC systems require narrowband lasers. Unfortunately, complex phase modulation systems and multi-stage amplifiers are needed to avoid stimulated Brillouin scattering (SBS) effect. Therefore, the power of narrowband fiber lasers is limited to around 2 kW [7]. Comparing with the single-grating SBC, dual-grating SBC is less sensitive to the linewidth of individual lasers [8]. Two fiber lasers with a total output power of 190 W using dual-grating SBC was reported [9]. However, to the best of our knowledge, no dual-grating SBC with the power higher than kilowatts has been reported so far..

In this contribution we report on the beam combination of fiber amplifiers by simultaneously using dual-grating SBC and polarization combining. The typical characteristic in our configuration is that the fiber lasers are relatively broadband (compared to lasers used in single-grating SBC), the diffraction gratings are polarization sensitive. The configuration has significant scaling potential in terms of high power individual lasers and considerable channels.

2. Operation concepts

The experimental setup, depicted in Fig. 1, begins with five master oscillators with different wavelengths. They are followed by five fiber amplifiers using non-PM Yb-doped fiber. Each of laser beams is amplified to 1.1 kW and expanded to a Gaussian-like beam with the diameter of $2\omega_0$=3 mm. Then the beams are all collimated and propagating parallel to each other. All of the beams are split into two

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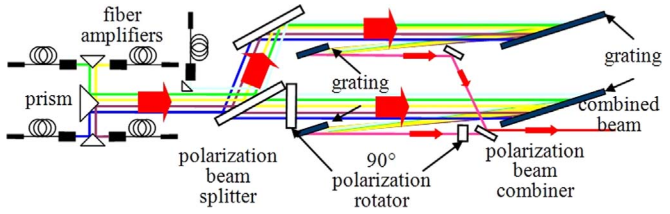

Fig. 1. Experimental setup of the hybrid combining experiment of five fiber laser amplifiers.

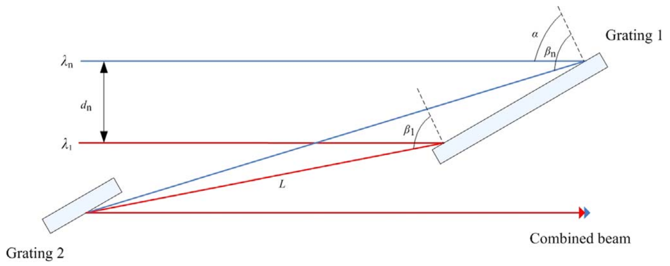

Fig. 2. Relevant angles and distances in the dual-grating SBC system.

Table 1
Parameters of hybrid combining experiment of five fiber laser amplifiers.

Wavelength (nm)	Distance (mm)	Diffraction angle (°)
1060.59	0.00	69.90
1062.57	9.78	70.49
1063.98	17.28	70.91
1065.50	25.93	71.38
1067.44	37.95	72.00

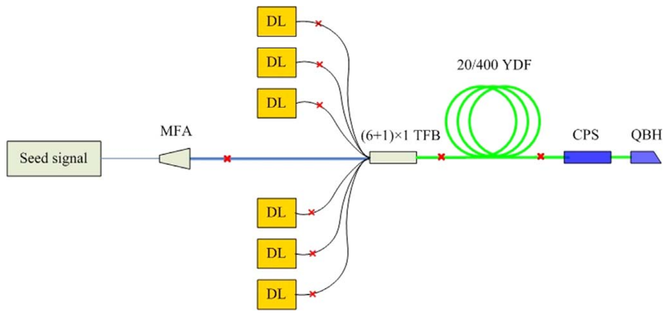

Fig. 3. Experimental setup of monolithic narrow line fiber amplifier system.

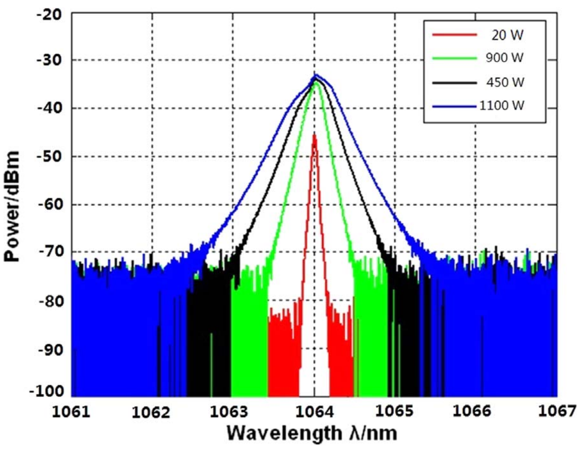

Fig. 4. Output spectrum of a typical fiber MOPA laser at different power levels.

orthogonal linearly polarized beams by a polarization beam splitter. Two channels of beamlets (s- and p- polarization components) are spectrally combined into a single beam respectively by dual MLD gratings (fabricated by University of Science and Technology of China). The gratings are polarization sensitive, only s-polarization could be effectively diffracted. So the polarized direction of p-polarization beams are rotated 90° before SBC by a polarization rotator. Another polarization rotator is used to reset the beams to p-polarization for polarization combination. The distances between each beam are carefully calibrated so that all the beams can be overlapped on the second grating. Finally, a polarization beam combiner is used to combine two polarization channels. As a result, the far-field and near-field of all the five beams are fully overlapped and no active adjustment is required.

Our dual-grating SBC configuration is illustrated in Fig. 2. Different from Ref. [9], the diffraction angle is bigger than the incident angle in order to make full use of the dispersion ability of the grating. In the same spectral range, more laser beams can be combined, and the distance between the two gratings is shorter in our setup which means a significant reduction in system size.

For all the five beams, the incident angle (on the grating) is α=65°. The diffraction angle β_n for individual beam satisfies the grating equation

$$\Lambda(\sin\alpha + \sin\beta_n) = \lambda_n \tag{1}$$

where Λ=574.7 nm is the period of the MLD gratings (the groove density is 1740 lines/mm), λ_n corresponds to the central wavelength of the beams. For the optical distance between the two gratings (for λ_1) L=760.00 mm, the lateral distance between the first and n-th beam centers d_n can be calculated by the following equation [9].

$$d_n = \frac{(\beta_n - \beta_1)L\cos\alpha}{\cos\beta_n} \tag{2}$$

Other parameters in our layout are listed in Table 1.

The narrow linewidth fiber lasers are the key components of the high power SBC system. In our system, fiber MOPA laser consists of an FBG-based oscillator and single-stage amplification. Fig. 3 illustrates the experimental setup of a co-pumped narrow linewidth all-fiber MOPA. A fiber oscillator consists of a pair of FBG is used to provide the single mode seed signal. The seed signal with the maximal output of 20 W and a FWHM linewidth of 0.06 nm is launched into a mode field adapter (MFA) to match the mode field of the fiber in the amplifier. Then the MFA is spliced onto a (6+1)×1 tapered fiber bundle (TFB) which is connected with six 976 nm pump modules. The measured pump power after the TFB with full current on the diode banks is 1.4 kW. The TFB is then spliced onto 12 m of a large-mode-area (LMA) (20/400 μm) fiber with an absorption of 1.26 dB/m for 976 nm pump light. The numerical apertures of the core and cladding are 0.06 and 0.46, respectively. In addition, the cladding power stripper (CPS) is used to dissipate the power in the cladding and the quartz block head (QBH) is used in the end to eliminate signal reflection. The amplifier is generating 1.1 kW with a linewidth of 0.3 nm (FWHM), and the beam quality factor (M^2) is around 1.5.

Fig. 4 presents the output spectrum of a typical MOPA fiber laser at different power level. Due to the long interaction length in MOPA fiber laser, the strong fiber nonlinearity will occur and induce the linewidth broadening. Generally, FWHM value is used for the laser linewidth quantification. However, the stochastic characteristics of multi-longitudinal-mode laser may lead to a non-Gaussian shape power distribution of each mode. In a dual-grating configuration, beam quality degradation and linewidth are correlated. As the beam quality is quantified by 1/e^2 values of beam diameter, 1/e^2 linewidth are preferable as they result in simpler calculations. In this case, the measured 1/e^2 linewidth of each laser beams is approximately 0.5 nm at 1.1 kW.

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